

LIFTING-BODY RESEARCH VEHICLES IN A LOW-SPEED FLIGHT TEST PROGRAM

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DESCRIPTION OF THE PROGRAM

Research on lifting-body configurations has been in progress for many years. About four years ago, the NASA Flight Research Center became interested in flight testing this concept. At that time many shapes were being formulated. The M-2 shape was chosen for construction because it had the most wind-tunnel data available. A low-wing-loading vehicle was chosen over the higher wing loading of a reentry vehicle to keep the overall cost in money, manpower, and time to a minimum. A large portion of the vehicle was designed and fabricated at the Flight Research Center and assembled to a plywood M-2 shell built to the Center's specifications by a glider manufacturer.

After assembly, the lightweight vehicle was taken to the NASA Ames Research Center for tests in the 40- by 80-foot wind tunnel. Approximately 80 hours of wind-tunnel tests were made. Since then, the lightweight vehicle has been flown approximately 500 times. Over 400 of the flights were ground tows using a high-powered tow car, and 85 flights were air tows using a C-47 as a tow plane. The cost of this program for the vehicle flight testing, including ground and air tows, was approximately \$50,000.

Because of the success of the lightweight M-2 project, it was decided to extend the research program to include vehicles that would be representative of mission weight and wing loading.

(H-408)



Some objectives that could be fulfilled during this flight program are as follows:

Investigation of the approach, flare, and landing characteristics, such as minimum landing L/D requirements, pilot procedures, and rocket-augmentation studies.

Evaluation of flight characteristics of the lifting-body class of vehicle.

Determination of general and specific flight-control-system requirements to allow the pilot to perform his assigned tasks.

Correlation of wind-tunnel and flight characteristics, such as drag, hinge moments, and basic stability and control data.

With these objectives in mind, it was decided to build two vehicles, primarily because of the desirability of having a backup for any vehicle in a flight test program. Even though the Ames M-2 and the Langley HL-10 lifting-body configurations differ considerably in their geometric and aerodynamic characteristics, either could be used to obtain data for the relatively thick blunt bodies characterized by their shapes. Since they do represent two different approaches to the lifting-body shapes and both show promise as future reentry vehicles, it was decided to make one of each instead of two of one shape.

A comparison of the three test vehicles discussed is shown in figure 1. Some of the changes between the vehicles, other than the increase in weight and wing loading, are:

Moving the canopy forward on the M-2 to improve landing visibility and to allow for ejection when mated to the underwing pylon of the B-52 launch airplane.

Removing the elevons from the vertical stabilizers of the M-2, which was necessitated by consideration of the heating problems



associated with those surfaces for a reentry vehicle. These surfaces produced an appreciable amount of the total lift (15 to 20 percent), and their removal reduced the lift-drag ratio of the basic vehicle.

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Extending the boattail by approximately 10 percent of body length, in an effort to recover some of the lost lift-drag ratio. In addition, a rudder-aileron interconnect will be utilized in an attempt to maintain roll response characteristics similar to the lightweight M-2.

Making the fixed landing gears, which contributed to the overall drag, extendable on the M-2 and on the HL-10.

Utilizing modern conventional aluminum structure in the M-2 and the HL-10 vehicles, rather than the old-time aircraft construction methods used for the lightweight vehicle.

Using a full irreversible, dual hydraulic, stability augmented control system in the M-2 and the HL-10 vehicles in contrast to the manual control system on the M-2.

As indicated in the figure, a planform area of 160 square feet was used as a basis for construction of both the M-2 and the HL-10 vehicles. A transverse section would show that the M-2 has a flat top with a curved bottom and that the HL-10 has a curved top with a flat bottom. The vehicles weigh approximately the same and have ballast tanks that will allow them to vary their weights from 4700 pounds to 9600 pounds, thus making it possible to simulate the wing loading of a reentry vehicle.

The controls on the M-2 consist of two upper surfaces for elevon control, a lower surface for pitch control, and dual rudders. The HL-10 has two elevons, a single rudder, and six movable stabilizing surfaces.

Another obvious difference between the vehicles is the canopy arrangement-a bubble canopy on the M-2, and a flush canopy on the HL-10.

A photo of the M-2, which has been delivered, is shown in figure 2(a), and a photo of the HL-10 in its construction jig at Northrop-Norair is shown in figure 2(b). The construction technique of both the M-2 and the HL-10 is similar; experimental shop methods were used throughout the program, with close coordination between engineering and fabrication.

The subsystems of the M-2 and HL-10 vehicles were made as similar as possible to allow for maximum utilization of spares, and the contractor was required to use as many "off the shelf" items as possible. Delivery of the HL-10 is expected during the middle of January.

The decision to build vehicles with higher wing loading (capable of being air launched from a B-52, similar to the X-15 operation) generated a requirement for further lifting-body research. The joint operation between NASA's Flight, Ames, and Langley Research Centers required a considerable amount of wind-tunnel testing and data analysis to define the specific vehicle shapes and their expected flight characteristics.

Ames Research Center supplied the Flight Research Center with M-2 shape and wind-tunnel data needed to design the M-2. They also provided the full-scale tunnel in which the lightweight and heavyweight M-2 vehicles have been tested and in which the HL-10 will be tested.

Langley Research Center supplied the shape data for the HL-10 and other wind-tunnel data as needed to design and construct the vehicle. They have also conducted an extensive wind-tunnel investigation of the launch conditions of both the M-2 and HL-10, and are conducting spin tests for both vehicles.

To the Flight Research Center fell the job of assembling enough data, not only from Ames and Langley, but from in-house simulator studies to accomplish its job of defining the flight control system and supplying the contractor, Northrop-Norair, with enough specifications and data to design and construct the vehicles.





The flight operational aspects of the M-2/HL-10 program will be carried out jointly with the Air Force Flight Test Center, similar to the joint activities on the X-15 program. The first flights will be captive flights. Figure 3 shows the M-2 mated to the B-52. These flights will check out the vehicle systems in their flight environment. The first free flights will check the basic longitudinal and lateral-directional stability and launch dynamics at a low weight condition and at a forward center of gravity with the stability augmentation system engaged and disengaged.

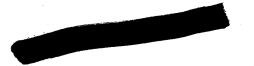
Future flights will determine the effects of wing loading on launch, glide, and landing. Flights will also be needed to determine the effects of an aft center of gravity at low and high wing loadings. During these heavyweight conditions, the pilot can jettison ballast to change the center of gravity and wing loading in flight if an unsafe condition exists. A minimum of 16 glide flights is planned.

When the glide flight program is completed, approval will be requested from NASA Headquarters for an extended flight program. This extension was anticipated, and during fabrication, the contractor was requested to incorporate provisions for XLR-ll rocket installations in the M-2 and HL-10 vehicles. (This engine was used in the X-l series of airplanes and the early X-15 flights.) The utilization of this capacity to extend the flight program depends upon a successful completion of the glide program.

The predicted flight envelope is shown in figure 4. The lightweight flight envelope is shown extending from tow release at 13,000 feet and a velocity of 110 knots to a landing on Rogers Dry Lake.

The first series of flight tests for the M-2/HL-10 program will be glide flights, starting by launch from the B-52 at approximately 45,000 feet and a Mach number from 0.6 to 0.8 and ending by gliding subsonically to a landing.

The second phase of the flight program will be an investigation of the





transonic characteristics of the vehicles. The flight envelope, as shown, is limited by a minimum dynamic pressure of 50 pounds per square foot, because of minimum control effectiveness, and a maximum dynamic pressure of 400 pounds per square foot due to structural limitations. If all goes well, a maximum Mach number of 1.7 will be attained at an altitude of 80,000 feet, which places the vehicle in the terminal approach corridor of a mission vehicle returning from space.

Although lifting bodies have often been considered attractive and desirable for use in major programs (Apollo, for example) the lack of manned flight experience with such vehicles precluded their use. The Flight Research Center flight program was designed to obtain this flight experience in a step-by-step investigation.

First, the lightweight vehicle was conceived, designed, built, and flown. Then the higher-wing-loading M-2 and HL-10 vehicles were conceived, designed, and one of them has already been built. Soon they will be flight tested and, hopefully, in two years will provide some answers to the flight objectives.

RESULTS OF THE FLIGHT TESTS

Before discussing the flight program, it would be advantageous to consider the maneuvering phases of a lifting entry and describe how the subject flight program is related to these requirements.

Figures 5 and 6 illustrate the aerodynamic maneuvering available to a typical lifting body and the maneuvering phases as discussed herein. Figure 5 includes the orbit track over the Western hemisphere and the maneuvering area available immediately following retrofiring or reentry initiation. Also shown is the maneuvering track followed after retro in an attempt to reach the destination, Edwards. The small footprint labeled "terminal" is the maneuvering area available at Mach 6. Terminal maneuvering would begin when the vehicle was



acquired by the destination's tracking radar.

Figure 6(a) shows an enlarged view of the destination area with the terminal and approach footprints superimposed. Figure 6(b) shows the Edwards lakebed with the approach and preflare footprints. As is evident, the footprints rapidly diminish in size with decreasing velocity. The initial flight investigation was concerned only with this preflare maneuvering phase. The approach maneuvering phase was investigated later in the flight program.

Previous experience with the low-lift-drag-ratio vehicles at the Flight Research Center raised questions on the maneuverability and horizontal landing capability of these shapes. The lightweight vehicle was constructed to evaluate the capability of a pilot to perform these maneuvering tasks during actual flight. It is planned to investigate these same maneuvering phases in a vehicle with a representative mission wing loading.

Description of Vehicle

The vehicle used in flight tests is shown in figure 7, with pertinent dimensions. As noted previously, the vehicle was constructed in-house with the exception of the plywood hull. The primary internal structure utilized typical light-aircraft technology in a welded steel-tube arrangement. Light-aircraft wheels and nose gear were used. The flight vehicle was configured as close to the early M-2 reentry shape as possible. Blunt leading edges, required during entry due to reentry heating, were duplicated, even though they were not the most aerodynamically efficient in the velocity regime investigated. The control surface use was representative of the anticipated mission vehicle usage. The two vertical surfaces were used as directional controls, the four horizontal surfaces for longitudinal control, and the two outboard horizontal surfaces for roll control.

The cockpit canopy shown is not necessarily the same shape or in the same location as that for a mission vehicle. In fact, there may not be a canopy on



a mission vehicle. The canopy could have been omitted, but this would have dictated an optical landing system or a much larger window in the fuselage. The canopy was added, however, to give the pilot as good visibility as possible so that the primary flight test objectives—investigation of approach, flare, and landing—would not be compromised. The canopy was located in this area to maintain a proper center—of—gravity location with the pilot and ejection seat included.

The fixed landing gear are not characteristic of a reentry vehicle. For reasons of design simplicity and cost, however, the fixed gear was used. This did reduce the maximum lift-drag ratio during approach and flare and added conservatism to the demonstration that a pilot could successfully maneuver, flare, and land this vehicle.

The control system is a direct manual system. No stability augmentation was provided. The control system did include ground adjustment capability of gearing, forces, and displacements. In addition, the stick-to-surface arrangement could be varied.

A limited amount of data was recorded during flight. Figure 8 shows, on the left, some of the longitudinal data obtained in flight plotted against angle of attack and a comparison with wind-tunnel data. The agreement is good. The linearity of the lift and stabilizer trim curves illustrates the reason for the good longitudinal response noted by the pilots. The plot on the right compares the lightweight vehicle with two other well-documented vehicles in terms of a current longitudinal-stability criterion. As indicated, the M-2 falls in the same rating area as the other vehicles. The pilots considered the M-2 longitudinal stability and damping characteristics to be as good as many of the present-day high-performance fighter aircraft, even without artificial stability augmentation. The criterion, however, shows only a rating of fair. Apparently, the pilots were pessimistic before flight and overly impressed during flight,



and, thus, rated the vehicle higher than it should have been.

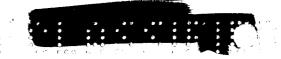
Figure 9 shows some of the flight-determined lateral-directional stability data plotted against angle of attack. The correlation with wind-tunnel data is not nearly as good as for the longitudinal data. However, the level of directional stability obtained in flight appears to be generally higher than predicted. The flight determined $C_{l\beta}$ shows considerable scatter but does indicate a relatively high positive dihedral effect. This has been obvious to the pilots during flight and has been the cause of some concern. The vehicle response to sideslip produced by gusts or turbulence is a rapid rolloff. The rate of rolloff is sensitive to the sideslip induced and has resulted in the restriction of flight operations to early mornings and light wind conditions.

The plot on the right in figure 9 is a recent criterion for lateral controllability, in terms of the Dutch roll stability $\omega_{\rm d}$ and the roll-coupling parameter ω_{ϕ} . The X-15 and the F-104 are shown for comparison. The M-2 tends to be sluggish in roll response. Dutch roll damping is only adequate. These two lateral characteristics are another reason for apprehension during encounters with gusts or turbulence.

The ability to obtain good roll characteristics conventionally in these low-aspect-ratio vehicles is limited because of the adverse yaw produced by aileron deflection and the vehicle response to yaw. On the other hand, rudder deflection can and does produce high roll rates due to the dihedral effect.

Most of these lifting-body configurations exhibit this high dihedral characteristic throughout a large angle-of-attack and Mach range. If rudder could be effectively used as a roll control, the aerodynamic control system could be simplified.

The use of rudder as a roll control was investigated in flight. The entire approach was flown using the rudder pedals. The results were good when small rudder inputs were used. The time history of figure 10 shows the vehicle



response to rudder deflection. As can be seen, however, larger and more rapid rudder inputs are confusing to the pilot because of the initial wrong direction of response, which makes their use unacceptable during and after flare when positive roll response is necessary for gust recovery and precise altitude control at touchdown.

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Figure 11 shows some of the performance data obtained in flight plotted against calibrated airspeed. The angle-of-attack range for the data shown is from -2° at 115 knots to 22° at 60 knots. The maximum angle-of-attack capability was intentionally limited to 22°, even though wind-tunnel data indicated linear longitudinal characteristics through 30°.

The maximum lift-drag ratio obtained in flight, 2.8, was somewhat lower than predicted by tunnel tests of the flight vehicle. It was, however, completely adequate to accomplish the necessary maneuvering and flare. Approach maneuvering was usually at velocities from 90 knots to 105 knots. Using a higher approach velocity than that for maximum lift-drag ratio provided the pilot with good control response in all axes due to the higher dynamic pressure. Also, when using this high approach velocity and low lift coefficient, the pilot had much additional lift available to increase normal acceleration and the rate of turn.

The preflare and landing velocities are also shown in figure 11. As indicated, the flare is initiated at high velocity. This high-energy preflare technique was developed and used successfully during the X-15 program. It provides the pilot with a large range of lift coefficient to vary normal acceleration and rate of flare and also provides some float time after flare. Touchdown occurs near maximum L/D while the vehicle is still at a relatively low lift coefficient. Although touchdown at this lift coefficient is necessary to prevent aft fuselage contact, because of the vehicle pitch attitude, it is also preferred by the pilots. Completing the flare and touchdown on the front

side of the L/D curve gives the pilot good flight-path response characteristics to control input. Flight in the back side region requires large control and angle-of-attack changes to obtain small flight-path changes.

Thrust Augmentation

Before the first free flight from altitude, a small solid-propellant rocket was installed. The rocket was oriented to provide longitudinal thrust and, in effect, to increase the lift-drag ratio. The rocket was added because of the uncertainty regarding the pilot's capability to adequately judge the flare, and the vehicle's inherent capability to complete a flare. The rocket was intended to provide a means of completing the flare successfully, even though the pilot initially misjudged both flare initiation and rate of flare. It was not required, however, since the pilot was able to flare the basic vehicle.

There has been some concern that a maximum lift-drag ratio of 3 might not be acceptable for operational missions. Thus, it was decided to investigate the effects of rocket thrust during flare. Seven flares were made using rocket thrust. Two different rockets were used, with 80 pounds and 160 pounds of thrust. Thrust duration for each rocket was 10 seconds.

Figure 12 compares some of the more important flare parameters during a normal flare and during a thrust-augmented flare (160-pound-thrust rocket). The most obvious result of thrust is the additional time available from flare initiation to touchdown. From the pilot's standpoint, this is desirable, since he can then use the additional time to adjust for good touchdown conditions. The reason for the additional time is indicated by the higher effective L/D, since the inverse of the L/D ratio determines deceleration. The rate of change of velocity is less during the augmented flare. The rocket thrust was less than 40 percent of the drag at maximum L/D, and the rocket weight was less than 2 percent of the vehicle weight. Yet, it almost doubled the time from flare initiation to touchdown. The results of these tests indicated that a



significant increase in effective lift-drag ratio can be obtained by using relatively low rocket thrusts. By providing thrust during flare only, the weight of the rocket can be less than 2 percent of the vehicle weight.

Heavyweight Vehicle Flight Test

The objective of the heavyweight M-2 flights will be to demonstrate vehicle stability and pilot controllability during the same maneuvering phases that were investigated with the lightweight vehicle. The predicted performance, stability, and control obtained from wind-tunnel tests indicate that the heavy-weight vehicle should be capable of the same maneuvering. There was some concern, however, about the effects of the different inertias on dynamic stability and controllability. Simulation results indicate that the change in inertias between the lightweight and heavyweight vehicles does not appreciably affect the capability of the pilot to control the vehicle. In addition, stability augmentation will be included in the heavyweight vehicle to assist the pilot. The primary question is the effect of wing loading on these maneuvering tasks.

The effect of wing loading on the approach pattern is illustrated in figure 13. The lightweight M-2 approach pattern is compared with that of the X-15 and the estimated heavyweight M-2 patterns. As indicated in the upper plot, horizontal distance tends to increase with wing loading. The lower plot shows an increase in high-key, or over the touchdown, altitude with increasing wing loading. X-15 experience has shown, however, that good touchdown accuracy (±2000 feet) can be achieved at these higher wing loadings.

The effect of wing loading on the flare is shown in figure 14. Again, the X-15 is included for comparison. As wing loading increases, the flare-initiation altitude increases. Also, as wing loading increases, the time available from flare initiation to touchdown increases. Though the heavyweight M-2 lift-drag ratio is less than that of the X-15, experience indicates that the time available

from flare initiation to touchdown in the heavyweight M-2 should be sufficient for the pilot to achieve acceptable touchdown conditions.

Concluding Remarks

The lightweight M-2 flight test program has demonstrated the capability of a pilot to control a lightweight lifting body during approach, flare, and landing. Further investigation is needed, however. Areas that are important, and that are being investigated, include the use of optical landing systems, night and instrument landing capability, and thrust-augmented flare. A serious effort is required to reduce the complexity of the aerodynamic control system to prevent the lifting reentry vehicle from being seriously compromised in weight.

• •	CITE ATTACK
12	SYMBOLS

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13	$\mathtt{C}_{\mathbf{L}}$	lift coefficient	
14	c _{lβ}	effective dihedral derivative	
15	C _{nβ}	directional-stability derivative	
16	h	altitude, ft	
17	L/D	ratio of lift to drag	
18	M	Mach number	
19	q	dynamic pressure, lb/sq ft	
20	S _{plan}	planform area, sq ft	
22	v	velocity, knots	
23	w/s	wing loading, lb/sq ft	
24	x,ÿ	horizontal distance downrange and crossrange, respectively, ft	
25	ά	angle of attack, deg	
26	$\delta_{ extbf{f}}$	upper pitch-flap deflection, deg	
27	$\zeta_{m{ heta}}$	damping ratio	
28	$\omega_{\mathbf{d}}$	Dutch roll stability parameter	

		v*.	
1	ω_{Φ}	roll-coupli	ng parameter
2	Subscript	ន :	
3	APP	approach	
4	MAX	maximum	
5	TD	touchdown	
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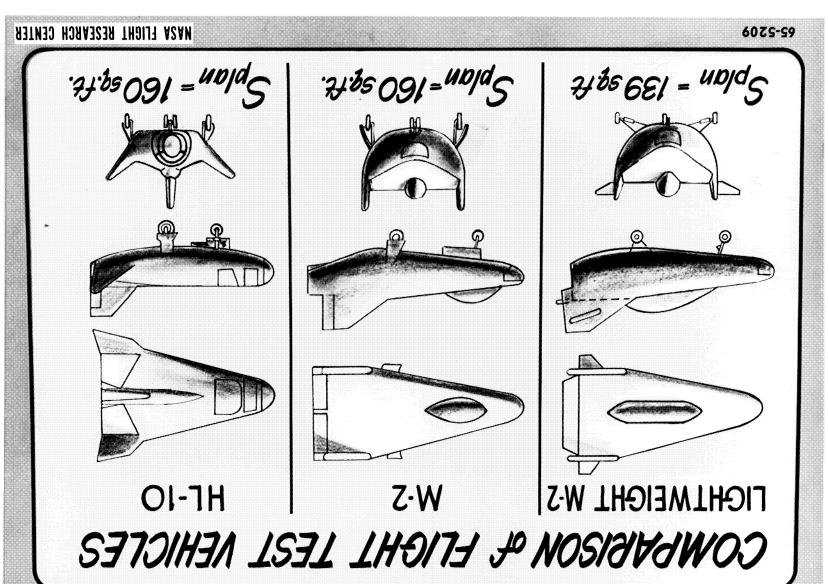
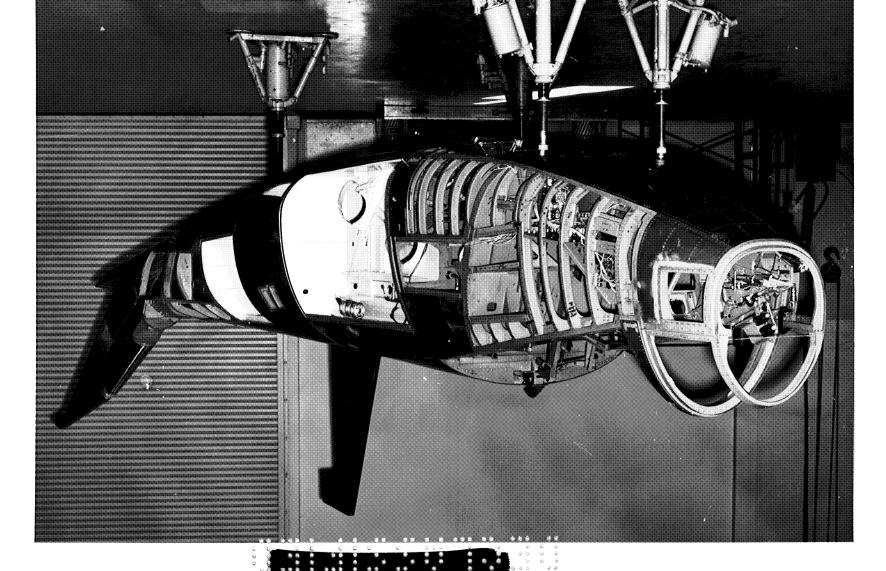




Figure 2(a)



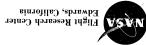


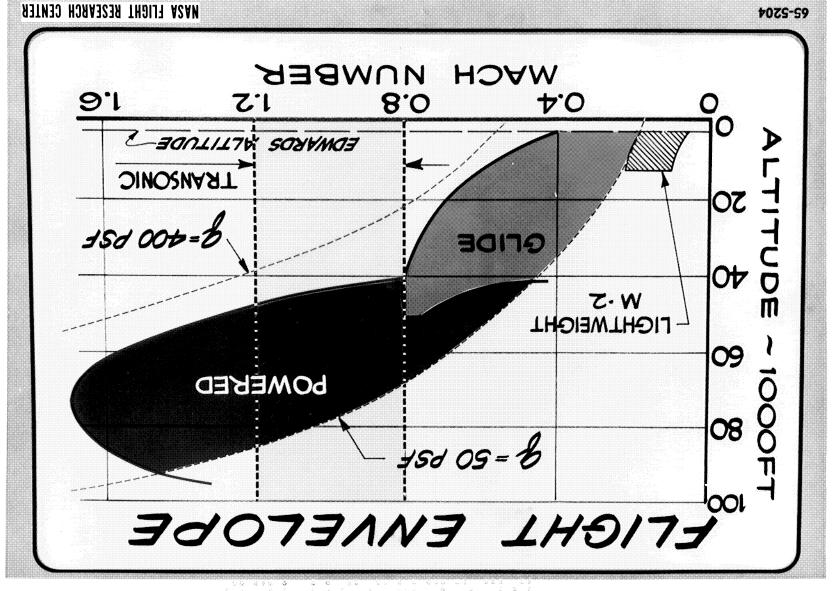


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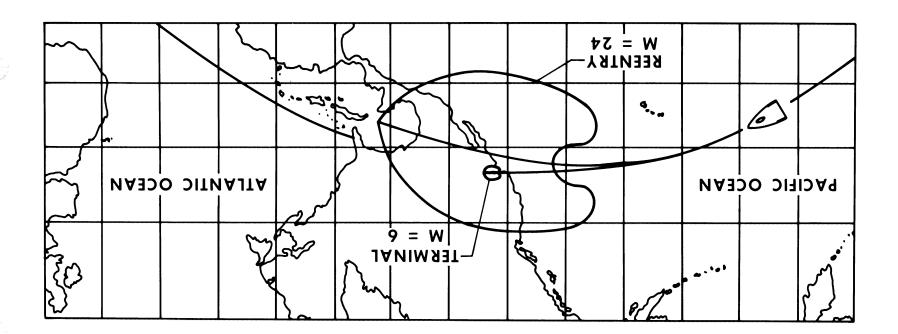


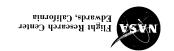


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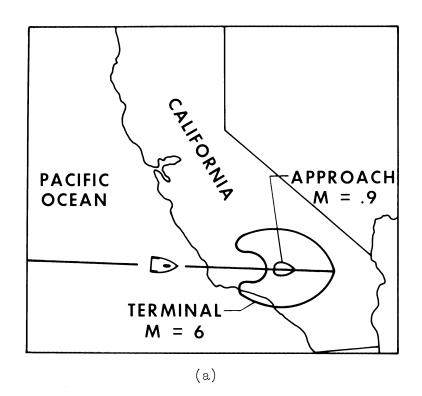
MANEUVERING FOOTPRINTS











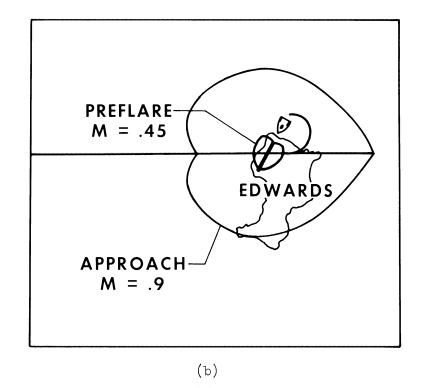
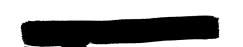
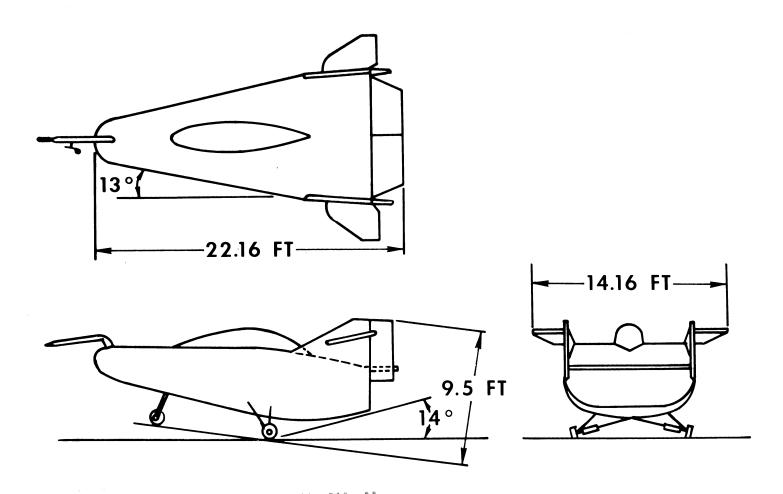


Figure 6



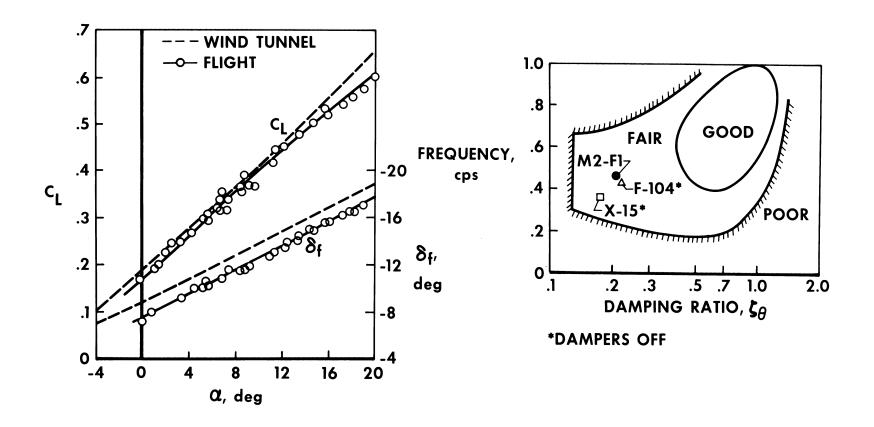


THREE-VIEW DRAWING OF LIGHTWEIGHT LIFTING BODY



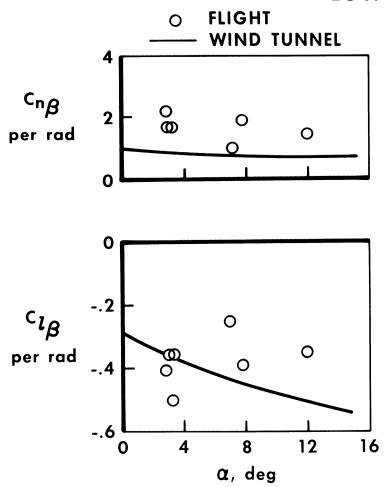
LONGITUDINAL CHARACTERISTICS

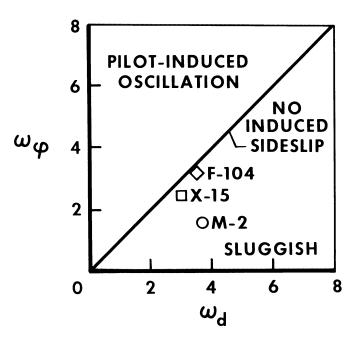
LIGHTWEIGHT LIFTING BODY LOW SPEED



DUTCH ROLL CHARACTERISTICS

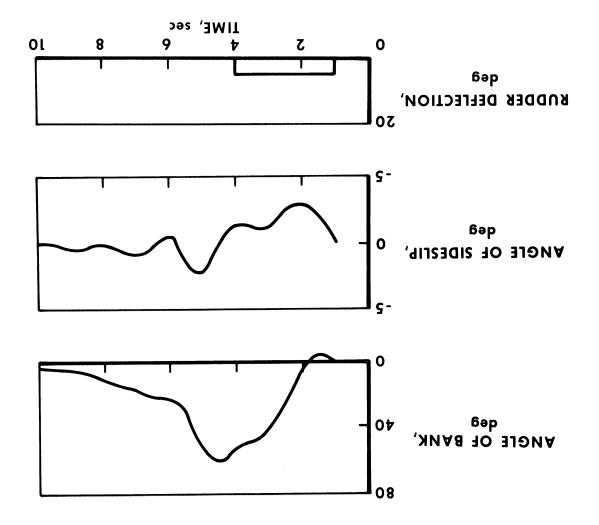
LIGHTWEIGHT LIFTING BODY LOW SPEED





Flight Research Center Edwards, California

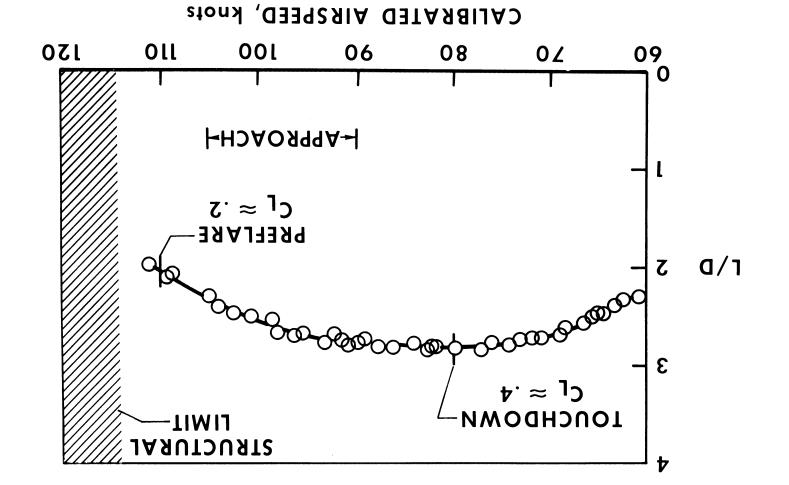




VEHICLE RESPONSE TO RUDDER INPUT

Flight Research Center Edwards, California

LIGHTWEIGHT LIFTING BODY



Flight Research Cent Edwards, California

FLARE TIME HISTORIES LIGHTWEIGHT LIFTING BODIES

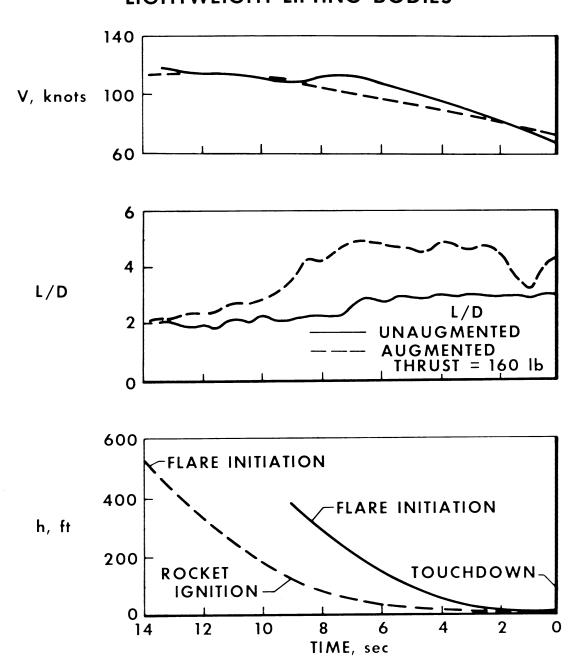
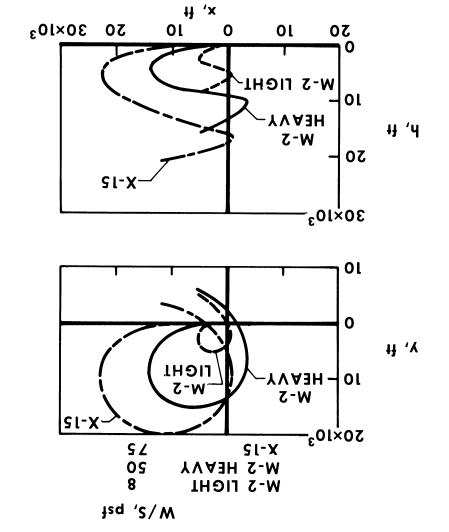


Figure 12

COMPARISON OF APPROACH PATTERNS





COMPARISON OF LANDING FLARES

